

Interpretation of the Flavor Dependence of Nucleon Form Factors in a Generalized Parton Distribution Model

J. Osvaldo Gonzalez-Hernandez,^{1,*} Simonetta Liuti,^{1,†}

Gary R. Goldstein,^{2,‡} and Kunal Kathuria^{1,§}

¹*Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.*

²*Department of Physics and Astronomy,
Tufts University, Medford, MA 02155 USA.*

Abstract

We give an interpretation of the u and d quarks contributions to the nucleon electromagnetic form factors for values of the four-momentum transfer up to few GeV where flavor separated data have been recently made available. The data show, in particular, a suppression of d quarks with respect to u quarks at large momentum transfer. This trend can be explained using generalized parton distributions which provide a correlation between momentum and coordinate spaces, both of which are necessary in order to interpret the partonic substructure of the form factors. We show that a flavor dependence originates from both Regge and quark-diquark terms in our model.

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*Electronic address: jog4m@virginia.edu

†Electronic address: sl4y@virginia.edu

‡Electronic address: gary.goldstein@tufts.edu

§Electronic address: kk7t@virginia.edu

A recent experimental analysis displays a flavor separation of the nucleon elastic electromagnetic form factors [1]. The data show both a suppression of the d quark contribution to the form factor with respect to the u quark at large momentum transfer. In this Letter we propose an interpretation of this somewhat puzzling behavior while simultaneously exploring the correlation between momentum and coordinate space of the Generalized Parton Distributions (GPDs) or, more precisely, the connection they provide between single-particle densities in both momentum and impact parameter space. This approach enables us to show how the flavor dependence originates from different components of our model, namely a contribution from reggeon exchanges, and a handbag contribution, or quark-diquark term.

GPDs define hybrid properties of the deeply virtual structure of nucleons [2–4]. Depending on the ranges of the defining kinematical variables ξ (skewness) and x (longitudinal momentum fraction), the GPDs, $H(x, \xi, t)$, can be interpreted at a given scale, Q^2 , as non-forward Parton Distribution Functions (PDFs), $x > |\xi|$, or Distribution Amplitudes (DAs), $x < |\xi|$. Lorentz invariance implies that their first moment in the initial parton's longitudinal momentum fraction, x , is ξ independent. It is the nucleon form factor,

$$F(t) = \int dx H(x, 0, t). \quad (1)$$

By Fourier transforming $H(x, 0, t)$ in the variable Δ_\perp ($t = -\Delta_\perp^2$), one obtains a single-particle density, or a diagonal object in impact parameter space, $\rho(x, \mathbf{b})$.

The formal backbone to this picture – the dominance of the handbag diagram – is provided by well established factorization theorems [3, 5]. The models which render a QCD description on how to interpret the parton correlators both in the forward and non-forward cases, and on how to establish the dominant degrees of freedom and their relative roles, are, however, debatable. Reviews on both the history and the more recent important developments on this longstanding issue, focusing on elastic scattering, can be found in *e.g.* [6–8].

Here we proceed by introducing a GPD perspective in this debate. In [9] we developed a model in order to interpret Deeply Virtual Compton Scattering (DVCS) data. The model is a realization of the reggeized quark-diquark picture [10], in which Regge behavior of the GPDs is incorporated by introducing a spectral distribution for the spectator diquark mass. Upon integration over the mass, the spectral distribution yields on one side the desired $x^{-\alpha}$ behavior, and on the other, it is consistent with the diquark model (Fig.1a,b).

The need for introducing a Regge term while applying diquark models to GPDs was realized in previous studies [11]. There it was noticed that while it is a known fact that the diquark model cannot produce a steep enough increase of the structure functions at low x , this might be of minor importance in kinematical regions centered at relatively large x where most data in the multi-GeV region are. It is however a necessary contribution in order to obtain the normalization of the structure functions correctly. This observation becomes

important for GPDs where we require them to reproduce the form factor's behavior exactly through their normalization, or first moment as given in Eq.(1). The Regge term is therefore an essential ingredient in model building. The importance of the Regge term was realized recently also in Refs.[12, 13]. There, however, the more singular behavior is introduced with a slightly different motive – it is required in order to model GPDs from a single Double Distribution.

In practical terms, our reggeized diquark model depends on a number of parameters that we divide into Regge and pure diquark contributions, as we will explain in more detail below. The parameters were fixed by a fit applied recursively to PDFs from deep inelastic scattering data, and to form factors and DVCS data from Jefferson Lab [14]. The model was subsequently compared to data on different observables (charge and transverse single spin asymmetries), in a different kinematical regime from HERMES [15, 16]. We define our parametrization as “flexible” in that, mostly owing to its recursive feature, the different components can be efficiently fitted separately as new data come in.

Summarizing, we consider Ref.[9] as the accomplishment of a first phase in which we constructed a reggeized diquark model which satisfies fundamental requirements, such as polynomiality, positivity, crossing symmetries, hermiticity, and time reversal invariance. In the process, we studied the behavior of the various parameters both for the forward limit and for the integral relations including form factors, and we reproduced a number of observables. Our main result is summarized in Table I of Ref.[9] where an optimal set of the parameters obtained from data available at the time of publication was presented.

With a viable model in hand we can now move on to understanding the role and interplay of its different components in interpreting a variety of experimental data. In particular, since the t dependence arises naturally in our model, namely it is not superimposed *ad hoc*, we can understand what features of the GPDs can simultaneously fit the PDFs and feed into the form factors. Why can, for instance, our flexible model reproduce the flavor dependence of the nucleon form factors? What components dominate – Regge or diquark, and for what values of t ? What aspect of the nucleon substructure can this be traced back to?

In Ref.[1] the u and d quarks contributions to the nucleon form factors were extracted for the first time up to values of t in the few GeV region, using isospin symmetric decomposition formulae,

$$F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n \quad (2a)$$

$$F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p \quad (2b)$$

where, as usual, $F_{1(2)}^u$, and $F_{1(2)}^d$ are the Dirac and Pauli u and d quarks contributions to the proton form factor. The data show the somewhat surprising results that at the largest t the

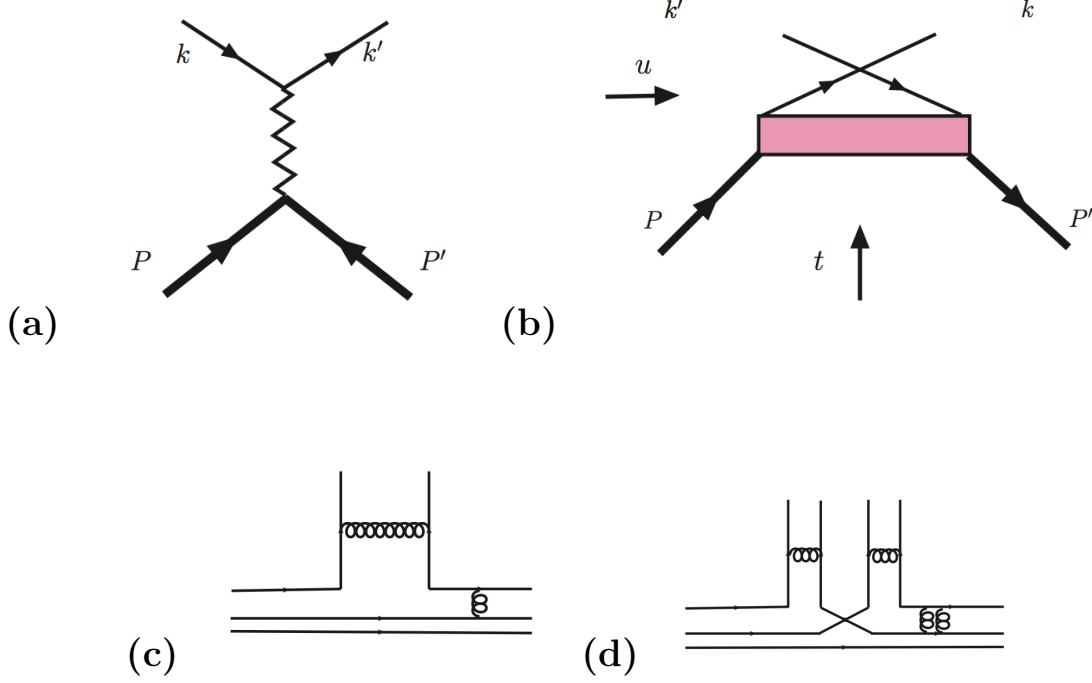


FIG. 1: (a) t -channel Reggeon exchange diagram; (b) u -channel diquark exchange. The box has mass M_X , with spectral distribution $\rho(M_X^2)$ as described in the text; (c) the same as (a) and (b) exhibiting the parton content; (d) Regge cut with its parton content corresponding to a diquark correlation.

contribution of the d quark is suppressed relative to u , for both F_1 and F_2 .¹

A re-fit of our model using the new data displayed in Fig.2 produced, first of all, the important result that we reduced the errors of our parametrized form for the GPD considerably. Our model can be summarized in this expression,

$$F(X, \zeta, t) = \mathcal{N} G_{M_X, m}^{M_\Lambda}(X, \zeta, t) R_p^{\alpha, \alpha'}(X, \zeta, t) \quad (3)$$

where $F \equiv H, E$; the functions $G_{M_X, m}^{M_\Lambda}$ and $R_p^{\alpha, \alpha'}$ parametrize respectively, the quark-diquark and Regge contributions; X and ζ are related to x and ξ by, $X = (x + \xi)/(1 + \xi)$, $\xi = 2\zeta/(2 - \zeta)$, however, here we are interested in the $\zeta = \xi = 0 \Rightarrow X = x$ limit. The diquark components read,

$$H_{M_X, m_q}^{M_\Lambda^q} = \mathcal{N} \int \frac{d^2 k_\perp}{1-x} \frac{\left[(m_q + Mx)(m_q + Mx) + \mathbf{k}_\perp \cdot \tilde{\mathbf{k}}_\perp \right]}{[\mathcal{M}_q^2(x) - k_\perp^2/(1-x)]^2 [\mathcal{M}_q^2(x) - \tilde{k}_\perp^2/(1-x)]^2} \quad (4a)$$

$$E_{M_X, m_q}^{M_\Lambda^q} = \mathcal{N} \int \frac{d^2 k_\perp}{1-x} \frac{-2M/\Delta_\perp^2 \left[(m_q + Mx) \tilde{\mathbf{k}}_\perp \cdot \Delta_\perp - (m_q + Mx) \mathbf{k}_\perp \cdot \Delta_\perp \right]}{[\mathcal{M}_q^2(x) - k_\perp^2/(1-x)]^2 [\mathcal{M}_q^2(x) - \tilde{k}_\perp^2/(1-x)]^2} \quad (4b)$$

¹ It should be also noticed that both trends appear by extrapolating the widely used form factors parametrization by Kelly [17] to large t .

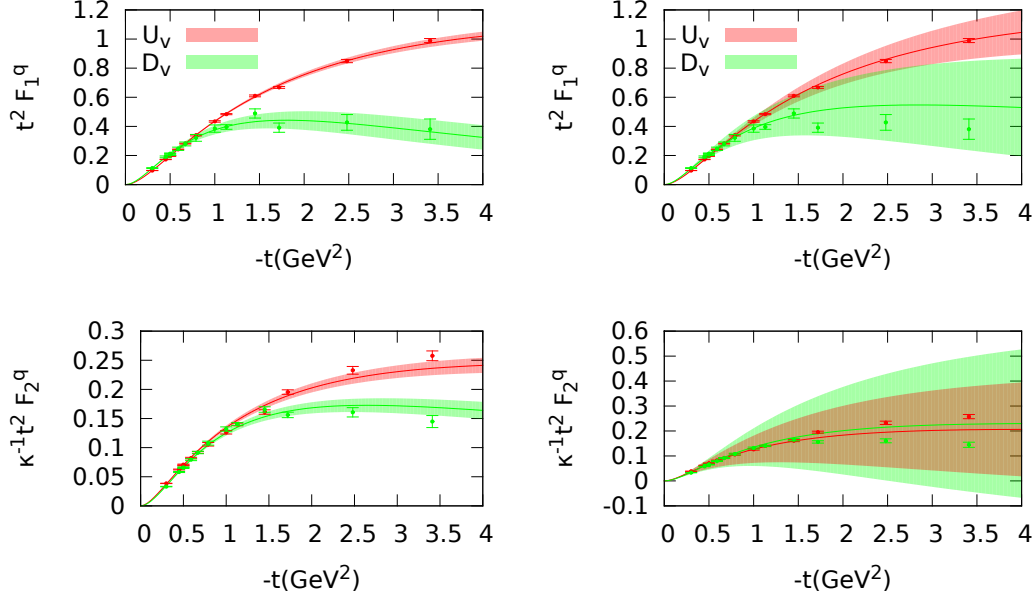


FIG. 2: Left Panel: Proton form factors $t^2 F_1^q$ (above) and $\kappa_q^{-1} t^2 F_2^q$ (below) plotted vs. $-t$, as obtained from our parametrization using Eq.(3), by fitting the data preceding Ref.[1]. Right Panel: same as Left, including the data from Ref.[1]. The parametrization's error bands were obtained without taking into account parameters correlations. Experimental data on both panels are from Ref.[1].

where $q = u, d$, \mathcal{N} is in GeV^4 , $\tilde{\mathbf{k}}_\perp = \mathbf{k}_\perp - (1-x)\Delta_\perp$, $\mathcal{M}_q^2(x) = xM^2 - x/(1-x)M_X^{q2} - M_\Lambda^{q2}$, M being the proton mass.

The Regge term is given by

$$R = \mathcal{N} x^{-[\alpha + \alpha'(x)t]}, \quad (5)$$

where $\alpha'(x) = \alpha'(1-x)^p$.

Notice that while Eqs.(4) and (5) are displayed in a compact form that is suitable for a parametrization, they also represent the final outcome of a model integrating significant physical information from both quark-diquark correlations, and Regge behavior.

Eq.(3) corresponds to a generalization of the diquark picture in which the mass of the diquark, M_X^q is not fixed, but has a spectral distribution, $\rho_R(M_X^2) \propto (M_X^q)^{2[\alpha + \alpha'(x)t-1]}$,

$$\begin{aligned} F(X, \zeta, t) &= \mathcal{N} \int_{\overline{M}_X^2}^{\infty} dM_X^2 M_X^{2[\alpha + \alpha'(x)t-1]} G_{M_X, m}^{M_\Lambda}(x, 0, t) \\ &= \mathcal{N} x^{-[\alpha + \alpha'(x)t]} \int_{\bar{z}}^{\infty} dz z^{[\alpha + \alpha'(x)t]} G_{M_X, m}^{M_\Lambda}(x, 0, t) \Big|_{x=z/M_X^2} \\ &\approx \mathcal{N} x^{-[\alpha + \alpha'(x)t]} G_{M_X, m}^{M_\Lambda}(x, 0, t). \end{aligned} \quad (6)$$

where the superscript q is omitted for simplicity, and the variable M_X^2 in $G_{M_X, m}^{M_\Lambda}$ has been replaced with $z = xM_X^2$ (more details will be given in future work).

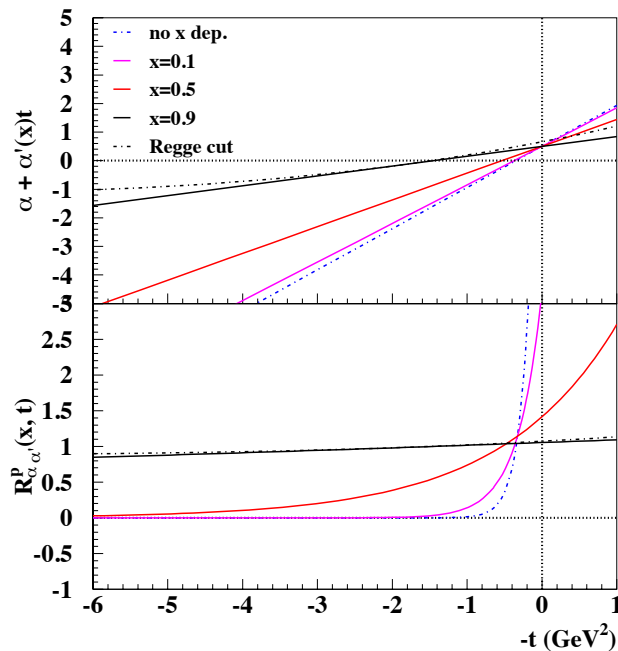


FIG. 3: (color online) Combined x and t dependences of the Regge contribution in our model (Eq.(5) and discussion in text). Upper panel: trajectories with x -dependent parameters from our model. The dot dashed line is a comparison with the softening of the slope first suggested in Ref.[20, 21]. Lower panel: Regge term, Eq.(5) obtained using the trajectories shown in the upper panel.

The Regge term has different interpretations in different kinematical regions:

$\zeta = 0, t = 0$ As first shown in Ref. [10] in a simple covariant model for PDFs, choosing a spectral distribution of the form $\rho_R(M_X^2) \propto M_X^{2\alpha(0)}$ gives rise to the behavior $x^{-\alpha(0)}$ upon integration over all M_X^2 . In Ref.[9] we illustrated the “reggeization” procedure by considering the forward, spin independent GPD, $H_q(x, 0, 0) = f_1^q(x)$, as a function of a continuum of diquark masses. Aside from overall constant factors, we obtained the expression for $\zeta = 0$ displayed in Eqs.(5) and (6).

$\zeta = 0, \text{small } t$ The result from Ref.[9] can be trivially extended to $t < 0$, noticing that the integrals are done at fixed t . So long as $\alpha + \alpha'(x)t$ remains positive, *i.e.* for $-t < \alpha/\alpha'(x)$, the physical interpretation remains unaltered because the behavior of the M_X^2 spectrum does not change considerably. This is the region spanned in DVCS-type experiments, where the reaction’s four-momentum transfer $Q^2 \approx (\text{few GeV}^2)$, and $-t < 1 \text{ GeV}^2$.

$\zeta = 0, \text{larger } t$ Larger, but not asymptotic, negative t can still be consistent with Regge behavior. The x -dependence of the slope parameter, $\alpha + \alpha'(x)t$, is such that it softens the fall off of the trajectory with negative t . Although this term was initially introduced driven by the need to guarantee more flexibility in parametrizations upon Fourier transformation in Δ_\perp [11, 18, 19], we are now able to interpret it physically: $\alpha'(x)$ effectively describes Regge

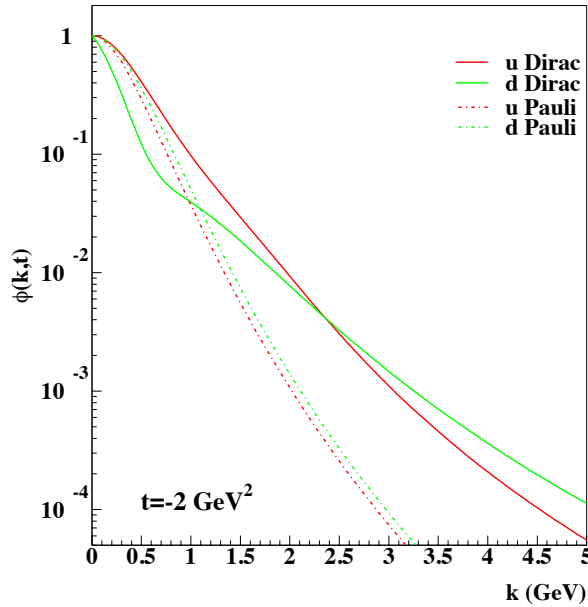


FIG. 4: (color online) Diquark vertex function contributions to the Dirac and Pauli form factors described in text.

behavior, including an important deviation from naive Regge, namely the appearance of cuts. The behavior with t is illustrated in Fig.3. It is interesting to relate this to the partonic structure that gives rise to Regge behavior represented in Fig.1c,d. Fig. 1c corresponds to a simple Reggeon exchange while Fig. 1d exhibits a Regge cut. Notice that the non-planar structure of this graph allows us to interpret the intermediate region as given by coupling of diquarks to the virtual photon. A similar contribution was considered in the Poincaré covariant Dyson-Schwinger equation (DSE) approach of Ref.[6], which includes both dressed quark and diquark components coupling to the virtual photon.

$\zeta \neq 0$ Including skewness, $\zeta \neq 0$ is more complicated, as singularities at the crossover point, $X = \zeta(x = \xi)$, might arise. This issue has been extensively discussed recently in [12] in the context of Double Distributions (see also [13]), although in the $t = 0$ limit. Detailed evaluations of the $\zeta \neq 0$ case do not enter the form factors picture, and will be presented elsewhere.

We now turn to the quark-diquark component by highlighting the angular momentum structure of the diquark correlations, given in this case by the $J^P = 0^+$ (scalar) and $J^P = 1^+$ (axial vector) configurations. From these one obtains distinct predictions for the u and d quarks contributions using a SU(4) symmetric wave function for the proton (see *e.g.* [22]),

$$F^u(X, \zeta, t) = \frac{3}{2}F^{S=0}(X, \zeta, t) + \frac{1}{2}F^{S=1}(X, \zeta, t) \quad (7)$$

$$F^d(X, \zeta, t) = F^{S=1}(X, \zeta, t). \quad (8)$$

From the practical point of view, one can take a similar form for the scalar and axial-vector couplings (scalar-like), while distinguishing their different contributions by varying their respective mass parameters as in Eqs.(4). This choice is motivated by previous work [11] showing that the full account of the axial-vector coupling does not sensibly improve the shape of parametrizations, while considerably increasing the algebraic complexity of the various structures.

Another important choice is in the form of the coupling at the proton-quark-diquark vertex. Consistently with studies of baryons in the context of the application of Dyson – Schwinger equations in QCD ([23] and references therein), we chose a dipole type coupling,

$$\Gamma = g_s \frac{k^2 - m_q^2}{(k^2 - M_\Lambda^{q^2})^2}, \quad (9)$$

where both m_q and M_Λ^q are among our fitted parameters. In Fig.4 we show the integrated wave function contributions, $\int dx \phi^*(x, k - \Delta) \phi(x, k)$, that enter the form factors calculation for a given value of $t = -2 \text{ GeV}^2$. One can see that for the Dirac form factor the u quark tends to dominate over the d quark while for the Pauli form factor the u and d quark contributions are similar to one another. The t dependence of this term is crucial in our model: at low t one finds a harder d quark component than for the u quark (analyses along these lines were initiated in Refs.[24, 25], where, however, the flavor dependence was not addressed).

The behavior in the different regions of t discussed above, as well as the diquark contribution to the nucleon form factors can be observed in the data through our fitting procedure [9]. In a first step we fitted $H^q(x, 0, 0)$, $q = u, d$ to the PDFs, $q(x)$, and obtained the parameters in Eqs.(4) and (5), M_Λ^q (Eq.(9)), \overline{M}_X^q (the starting point of the diquark mass spectrum), m_q (the quark mass), and α_q . The fit was performed by evolving to the scale, Q^2 of the deep inelastic data (in most formulae herewith we omit displaying Q^2 explicitly because it is not relevant to the discussion of the form factor). We used the same set of parameters for $E^q(x, 0, 0)$ since this is unconstrained at $t = 0$ (notice however that its functional form is different, Eq.(4b)).

Keeping these parameters fixed we obtained α' and p by fitting the Dirac and Pauli form factors

$$F_1^{p(n)}(t) = \int dx H^{p(n)}(x, 0, t) = e_{u(d)} F_1^{u(d)}(t) - e_{d(u)} F_1^{d(u)}(t), \quad (10)$$

$$F_2^{p(n)}(t) = \int dx E^{p(n)}(x, 0, t) = e_{u(d)} F_2^{u(d)}(t) - e_{d(u)} F_2^{d(u)}(t), \quad (11)$$

where $e_u = 2/3$, and $e_d = -1/3$. In Table I we show both sets of values for α' and p , using both the old set of data and the data from Ref.[1]. Results for both cases are displayed in

Parameters	H old data	H Ref.[1]	E old data	E Ref.[1]
α'_u	1.889 ± 0.0845	1.814 ± 0.0220	2.811 ± 0.765	2.835 ± 0.0509
p_u	0.551 ± 0.0893	0.449 ± 0.0170	0.863 ± 0.482	0.969 ± 0.0307
χ^2	0.8	0.9	0.7	4.8
α'_d	1.380 ± 0.145	1.139 ± 0.0564	1.362 ± 0.585	1.281 ± 0.0310
p_d	0.345 ± 0.370	-0.113 ± 0.104	1.115 ± 1.150	0.726 ± 0.0631
χ^2	0.8	0.5	0.7	3.2

TABLE I: Parameters obtained from our recursive fitting procedure applied to H_q , E_q , $q = u, d$. We obtained α'_q , p_q , by fitting the proton and neutron electromagnetic form factors. Also shown are the χ^2 values for the separate contributions to the fit.

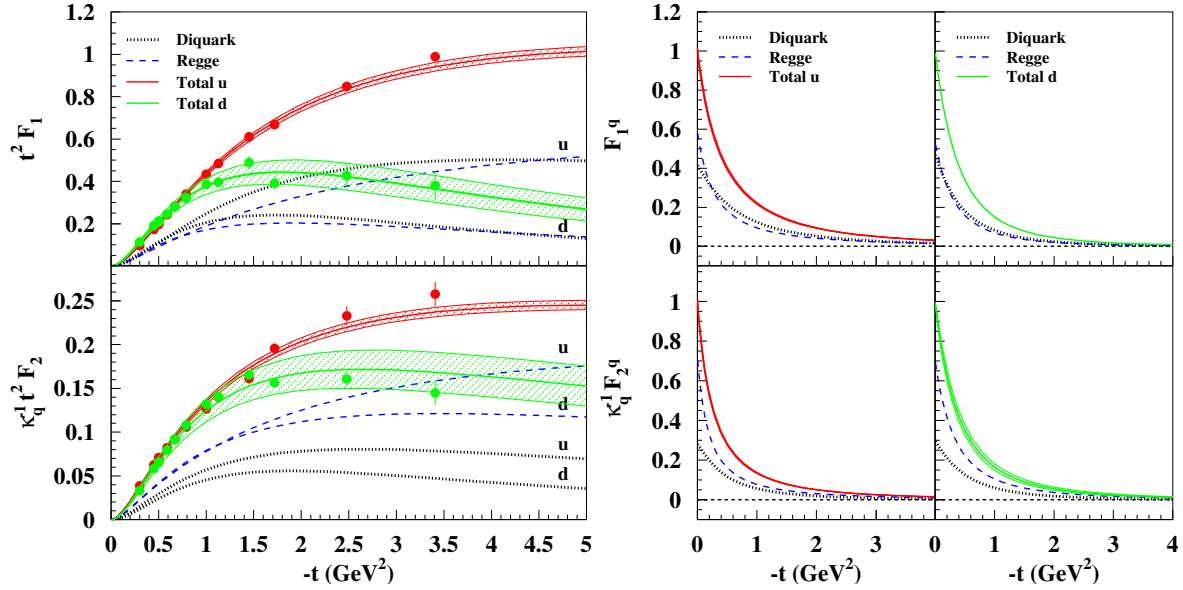


FIG. 5: (color online) Left Panel: $t^2 F_1^q$, $q = u, d$ (above) and $\kappa_q^{-1} t^2 F_2^q$ (below) plotted vs. $-t$, as obtained from our parametrization using Eq.(3). Right Panel: Proton form factors F_1^q , (above), u and d quarks contributions displayed in the left and right panels, respectively; $\kappa_q^{-1} F_2^q$ (below) Experimental data from Ref.[1]. The dotted lines correspond to the diquark contribution, Eq.(13); the dashed lines to the Regge contribution, Eq.(14).

Fig.2.

The nucleon form factors are decomposed in terms of u -quark and d -quark contributions, which in turn include a quark-diquark, and Regge term. The quark-diquark term describes scattering from a single, non-interacting u or d quark leaving either a ud diquark with spin $S = 0, 1$, or a uu diquark system with spin $S = 1$ as spectators. The Regge term describes scattering from a state which is effectively rendered coherent through Regge cuts, or diquark correlations (Fig.2d).

In order to ascertain whether the Regge component alone can drive the t -dependence, or

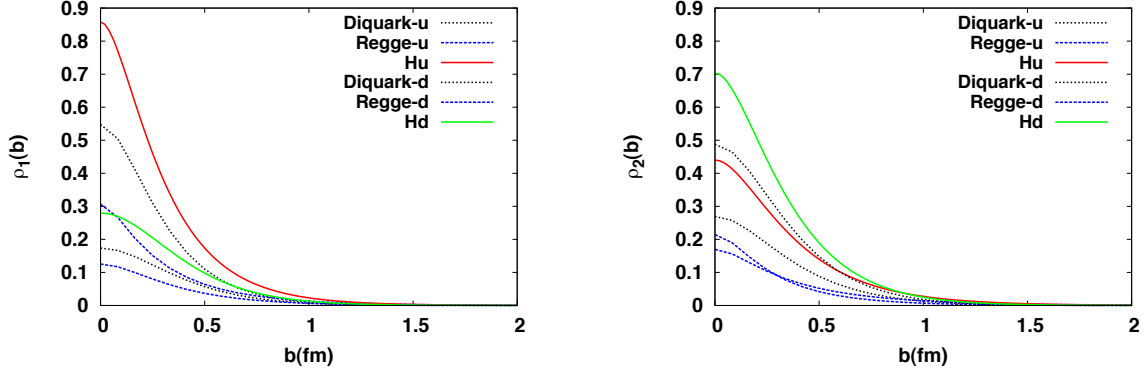


FIG. 6: (color online) Left Panel: Integrated parton density distribution in transverse space for the Dirac form factor, displaying all components of our model. Right Panel: same as left, for the Pauli form factor.

to determine its interplay with the t -dependent diquark term, we separated the Regge and diquark terms in the following way

$$F_q(X, \zeta, t) = F_G^q + F_R^q \quad (12)$$

where

$$F_G^q = \mathcal{N}_{G+R}^q G_{M_{X,m_q}^q}^{M_\Lambda^q} \quad (13)$$

$$F_R^q = \mathcal{N}_{G+R}^q R_{p_q}^{\alpha_q, \alpha'_q} \quad (14)$$

with $F_{G(R)}^q = H_{G(R)}^q, E_{G(R)}^q$; $\mathcal{N}_{G+R}^q = \left(1/R_p^{\alpha_q, \alpha'_q} + 1/G_{M_{X,m_q}^q}^{M_\Lambda^q}\right)^{-1}$.

Results for the Dirac and Pauli form factors calculated using Eqs.(13,14),

$$F_1^q = \int_0^1 dx (H_G^q + H_R^q), \quad (15)$$

$$F_2^q = \int_0^1 dx (E_G^q + E_R^q), \quad (16)$$

are shown in Fig.5. We notice that for the u -quark the Regge term does dominate the low t behavior as expected. For F_1^d the contributions of the Regge and diquark terms are instead comparable. The persistence of the Regge term at larger t where the form factors are dominated by large x [24] is not unexpected in our model, in view of diquark correlations/Regge cuts which extend the validity of the Regge model to this region (see Fig.3 and Refs. [20, 21]).

The Fourier transforms of GPDs with respect to Δ_\perp define the parton density distributions at a transverse position \mathbf{b} for a given longitudinal momentum fraction, x , namely two

dimensional distributions in the transverse plane with respect to the proton's direction of motion. We can therefore connect each form factor component to hadronic distances from the proton's center of momentum defined as [27],

$$\begin{aligned}
\langle b^2 \rangle_1^q &= \int_0^1 dx \int d^2b \rho_1^q(x, b) b^2 \\
&= \int_0^1 dx \int d^2b \left[\int \frac{d^2\Delta_\perp}{(2\pi)^2} [H_G^q(x, 0, \Delta_\perp^2) + H_R^q(x, 0, \Delta_\perp^2)] e^{i\mathbf{b} \cdot \Delta_\perp} \right] b^2 \\
&= \langle b^2 \rangle_{1G}^q + \langle b^2 \rangle_{1R}^q,
\end{aligned} \tag{17}$$

$$\begin{aligned}
\langle b^2 \rangle_2^q &= \int_0^1 dx \int d^2b \rho_2^q(x, b) b^2 \\
&= \int_0^1 dx \int d^2b \left[\int \frac{d^2\Delta_\perp}{(2\pi)^2} [E_G^q(x, 0, \Delta_\perp^2) + E_R^q(x, 0, \Delta_\perp^2)] e^{i\mathbf{b} \cdot \Delta_\perp} \right] b^2 \\
&= \langle b^2 \rangle_{2G}^q + \langle b^2 \rangle_{2R}^q.
\end{aligned} \tag{18}$$

In Fig.6 we show the density integrated over x , $\rho_{1(2)}^q(b)$ for all components. The behavior of the form factors at larger t is reflected in the behavior of ρ as $b \rightarrow 0$. One can deduce that Dirac hadronic sizes for the u quarks (Fig.6, left) are smaller than for the d quarks. A smaller difference between u and d quarks appears for Pauli hadronic sizes. For the quark-diquark component of our model one can easily trace back this behavior to the transverse momentum distribution, Fig.3, which is harder for the u quark than for the d quark. This is in turn a consequence of the difference in masses between the axial vector and scalar diquark which respectively govern the d quark and u quark contributions. Similar conclusions were reached in Ref.[6] although from different symmetry properties since they include also the longitudinal spatial component. The Regge term in our model is less straightforward to interpret, however, if we view it as a coherent state, then the distance involved in this case would be the combination of the two-quark, composite, hadronic component's size containing either the struck u or d quark, and the overall distance of this component from the proton's center of momentum.

In conclusion, we used a GPDs based approach as a way to understand the u and d quarks components of the nucleon form factors. The GPDs were evaluated using a reggeized quark-diquark model whose parameters are fixed to simultaneously fit the deep inelastic limit, the nucleon form factors, and DVCS data. In our approach both a Regge-type contribution and quark-diquark components determine the behavior of the form factors in the few GeV region. The Regge term is interpreted as effectively taking into account coherent processes, including final state interactions or Regge cuts. The latter are connected through duality to diquark correlations. As t increases we expect the Regge cuts to become suppressed, and the nucleon form factor to be dominated by Regge asymptotic behavior modulated by a t

dependent term. The quark-diquark term, on the contrary, involves scattering from a single quark, leaving a diquark system as a spectator (what happens in the center of the nucleon is determined by asymptotia which are not at reach in the kinematical domain of the data).

A first outcome is that the new highly precise form factor data produce much improved constraints on our GPDs parameters. The interpretation of the flavor dependence of the data lies in the non-perturbative structure of both the Regge and quark-diquark terms. It is a subtle combination of effects that cannot be ascribed to a single, simply motivated mechanism. We see on one side the persistence of notably flavor dependent Regge contributions at large t . Isovector exchanges present in our model are *e.g.* known to couple differently to u and d quarks. These terms alone produce a suppression of the d quark contribution with respect to the u quark. The Regge mechanism dominates the Pauli form factors.

Similarly, scattering from a single quark through the quark-diquark mechanism is flavor dependent, the d quark being suppressed because of the softer transverse momentum dependence of the proton-quark-diquark vertex function.

Through the concept of GPDs the Regge and diquark mechanisms are realized correspondingly in coordinate space, in the transverse plane where our description reflects the behavior of the form factors. Finally, a unified picture of the Regge and diquark contributions can be given using duality arguments. The Regge terms include a component that corresponds to diquark correlations in the nucleon. In the GPD picture one can also study the internal spatial distribution and size of these components.

The newly available flavor separated form factor data at large t stimulated this work. Further studies exploring a possibly important role of diquark/few-parton correlations inside the proton will be carried out in the near future.

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- [1] G. D. Cates, C. W. de Jager, S. Riordan and B. Wojtsekhowski, Phys. Rev. Lett. **106**, 252003 (2011)
 - [2] D. Muller, D. Robaschik, B. Geyer, F. M. Dittes and J. Horejsi, Fortsch. Phys. **42**, 101 (1994)
 - [3] X. D. Ji, Phys. Rev. D **55**, 7114 (1997)
 - [4] A. V. Radyushkin, Phys. Rev. D **56**, 5524 (1997)
 - [5] J.C. Collins, L. Frankfurt and M. Strikman, Phys. Rev. D **56**, 2982 (1997)
 - [6] I. C. Cloet, G. Eichmann, B. El-Bennich, T. Klahn and C. D. Roberts, Few Body Syst. **46**, 1 (2009)
 - [7] J. Arrington, C. D. Roberts and J. M. Zanotti, J. Phys. G G **34**, S23 (2007)

- [8] H. -y. Gao, Int. J. Mod. Phys. E **12**, 1 (2003) [Erratum-ibid. E **12**, 567 (2003)]
- [9] G. R. Goldstein, J. O. Hernandez and S. Liuti, Phys. Rev. D **84**, 034007 (2011)
- [10] S. J. Brodsky, F. E. Close and J. F. Gunion, Phys. Rev. D **5**, 1384 (1972).
- [11] S. Ahmad, H. Honkanen, S. Liuti *et al.*; *ibid* Eur. Phys. J. **C63**, 407-421 (2009); *ibid* Phys. Rev. **D75**, 094003 (2007).
- [12] A. V. Radyushkin, Phys. Rev. D **83**, 076006 (2011)
- [13] A. P. Szczepaniak, J. T. Londergan and F. J. Llanes-Estrada, Acta Phys. Polon. B **40**, 2193 (2009)
- [14] F. X. Girod *et al.* [CLAS Collaboration], Phys. Rev. Lett. **100**, 162002 (2008).
- [15] A. Airapetian *et al.* [HERMES Collaboration], JHEP **0806**, 066 (2008).
- [16] A. Airapetian *et al.* [HERMES Collaboration], JHEP **0911**, 083 (2009).
- [17] J. J. Kelly, Phys. Rev. **C70**, 068202 (2004).
- [18] M. Burkardt, Int. J. Mod. Phys. A **18**, 173 (2003)
- [19] M. Guidal, M. V. Polyakov, A. V. Radyushkin and M. Vanderhaeghen, Phys. Rev. D **72**, 054013 (2005)
- [20] P. D. B. Collins and P. J. Kearney, Z. Phys. C **22**, 277 (1984).
- [21] P.D.B. Collins and A.D. Martin, University of Sussex Press (1984).
- [22] H. Meyer and P. J. Mulders, Nucl. Phys. A **528**, 589 (1991).
- [23] C. D. Roberts, arXiv:1203.5341 [nucl-th].
- [24] A. V. Radyushkin, Phys. Rev. D **58**, 114008 (1998)
- [25] S. Liuti and S. K. Taneja, Phys. Rev. D **70**, 074019 (2004)
- [26] D. J. Wilson, I. C. Cloet, L. Chang and C. D. Roberts, Phys. Rev. C **85**, 025205 (2012)
- [27] G. A. Miller and J. Arrington, Phys. Rev. C **78**, 032201 (2008)